

Ensemble Assimilation of Nonconventional Observations for Nowcasting

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LONG-TERM GOALS

The final goal of this project is to provide the US Navy with an increased capability of using Doppler radar observations in the detection and prediction of hazardous weather events that usually have a strong randomness in nature and affect the Navy operations, especially over oceans and in remote areas. By developing a high-resolution data assimilation capability that can effectively assimilate Doppler radar observations along with other conventional and remotely-sensed data, the US Navy will have the ability to analyze and forecast the battlespace atmospheric conditions with sufficient detail and accuracy for supporting the Navy mission in threat detection, weapons deployment, and weather safe operations.

OBJECTIVES

The objective of the study is to develop an advanced ensemble-based radar data assimilation system for the US Navy and to address some critical scientific and technique issues associated with ensemble radar data assimilation. The radar data system that will be developed will use flow-dependent background error covariance (instead of the static background error covariance) to account for the complexity and rapid change in the dynamical and microphysical structures inside and outside storms. The system will assimilate all the observed variables from different types of sensors, including Doppler radars, satellites, UASs, and conventional meteorological observations, simultaneously to allow full interactions among the assimilated variables during the data assimilation to keep the balances among the dynamics, thermodynamics and microphysics in the model initial fields. The system will be able to use the observations from many types of radars on different platforms (WSR-88D, DoD meteorological radars and tactical radars both on-land and shipboard, etc.) with an appropriate quality control. Multi-scale data assimilation capability will also be one of the major features of the new radar data assimilation system that allows observational data at different scales to be assimilated concurrently to ensure the scale balance in the ensemble analyses.

APPROACH

The ensemble Kalman filter (EnKF) recently developed at NRL will be the major tool for this study. All the radar data processing and quality control systems previously developed at NRL will be extended to cover the ensemble-based data assimilation and integrated into the EnKF for radar data decoding, pre-processing, quality control, bias removal, and observational error estimation. The

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proposed ensemble radar data assimilation system will assimilate the raw Doppler radial velocity observations directly in the observational space. This will help to reduce the errors induced during the pre-retrieval and interpolation of wind vectors. A data thinning algorithm will also be developed for radar observations to reduce the data density (especially near the radar locations) and hence the data dependency before assimilation. In the last few years, NRL, NSSL and OU have jointly developed a data thinning algorithm for Doppler radial velocity. This algorithm will be further refined and used in the proposed ensemble radar data assimilation system. The NRL 3D Radar Mosaic will serve as the reflectivity data thinning algorithm.

The forward radar observation operators previously developed at NRL for the 3d/3.5d-Var will be adapted for estimating the radar observations in observational space from ensemble forecasts. For storm-scale data assimilation, one of the biggest challenges is the missing storms in the background fields so that there are no estimated radar observations available at observation locations for the data assimilation. The use of ensemble forecasts as the background should have some advantages over the use of a single deterministic forecast in this aspect. Appropriate ensemble spread that covers all the uncertainties of the model forecasts is critical.

Localization is a necessary step in all ensemble-based data assimilation systems to account for the insufficient ensemble size due to the lack of computational power. The length scale of the localization is a very sensitive parameter that affects the ensemble analyses. The assimilation of storm-scale data along with the large- and synoptic-scale observations makes this challenging issue even much more challenging. In this study, we will develop an observation-adaptive, variable-dependent, multi-scale localization algorithm. This algorithm will use a multiple-localization procedure and determine the localization scale based on observational data type, the control variable, and the statistics of the observational and background errors.

New algorithms will be developed that incorporate the dynamical and physical constraints from the variational methods into the EnKF to improve initial balance among the model fields and to reduce the spurious background error covariance outside observed storms caused by the zero/non-zero boundaries along the storm edges due to ensemble perturbations in storm location forecasts. The new hybrid technique will be built in the EnKF and should be computationally more efficient than the traditional hybrid data assimilation approach (that runs two systems in parallel), and is therefore more suitable for non-conventional, storm-scale sensor data assimilation.

WORK COMPLETED

In FY13, this project worked coordinately with the 6.4 COAMPS-OS[®] (sponsored by PMW-120) on the development of NRL radar data assimilation system at full scale with many achievements in real-time shipboard radar data acquisition, transition of the well-tested 3DVAR radar reflectivity data assimilation system to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for operation, preparation and testing of the 3.5DVAR radar wind data assimilation system for transition, and the development of advanced ensemble radar data assimilation techniques.

1. Acquisition of real-time HWDDC shipboard radar observations for data assimilation

Hazardous Weather Detection and Display Capability (HWDDC) technique developed at the Space and Naval Warfare Systems Command (SPAWAR) passively taps into the shipboard SPS-48E Air Control Doppler radar signal and creates volumetric weather radar data stored in Universal Format

(UF) files. Currently, about thirteen US Navy battleships have been equipped with HWDDC technique with seven more ships that will be equipped with HWDDC in next few years. These data provide three-dimensional observations of storms over oceans that can hardly be measured by conventional meteorological networks. By working closely with SPAWAR and FNMOC, NRL radar data assimilation team overcome many technical barriers and has got the HWDDC radar observations from four ships processed, compressed and transferred to FNMOC in real-time for assimilation into COAMPS-OS to improve storm prediction. Real-time HWDDC data from other ships are expected to be available at FNMOC in the coming years.

2. Transition of NRL radar reflectivity data assimilation to FNMOC

In a combined effort with the 6.4 COAMPS-OS project and also in collaboration with FNMOC, the variational radar reflectivity data assimilation system developed few years ago by NRL scientists (Zhao et al. 2008) has been transitioned to FNMOC for operation through COAMPS-OS version 2.4.0. The software package transitioned to FNMOC includes the NRL radar data processing and quality control suite, NRL 3D Radar Mosaic, and a 3DVAR reflectivity data assimilation system.

Before the transition, all algorithms were finalized, reconfigured based on operational requirements, and extensively tested in a real-time mode with data both from HWDDC shipboard radars and from the WSR-88D radar network. The pre-transition tests with HWDDC real-time data were conducted during the Navy exercises of RIMPAC and Valiant Shield 2012 to demonstrate the capability of assimilating shipboard “through-the-sensor” radar observations into the Navy’s high-resolution NWP model to improve storm forecast to support Navy operations. The tests with WSR-88D radar data were performed in 2013 with three separate domains over US, each with two or three nested grids. Figure 1 gives the West Atlantic (WATL) test domain with two nested grids with 45 km and 15 km grid resolutions, respectively. In this test domain, real-time radar reflectivity observations from more than 120 WSR-88D radars were collected and assimilated into COAMPS-OS two times a day.

3. Preparation and testing of NRL 3.5DVAR radar wind data assimilation for transition

The 3.5DVAR Doppler radial velocity data assimilation system was originally developed by Xu et al. (1995) for storm wind retrieval from Doppler radar observations. It was later implemented at NRL for COAMPS[®] model radar data assimilation jointly by scientists at the National Severe Storms Laboratory (NSSL) and NRL (Zhao et al. 2006, 2008; Zhao and Jin 2008; Xu et al. 2010) to improve severe weather forecasts to support Navy operations. Last year, the system was modified, further refined and reconfigured to reduce the memory size requirement and to improve computational efficiency for operational applications. The major change to the system was the removal of the requirement for COAMPS restart function, which is no longer supported by the model development team. Instead, the new version uses COAMPS flat format files as inputs. Currently, the system is under extensive test.



Figure 1. The WATL 45 km and 15 km grid domains for the real-time test of the 3DVAR radar reflectivity data assimilation system before the system transition to FNMOC. The locations of the WSR-88D radars, from which real-time level-II data were collected and used in the test, are indicated as “+” on the map and the while circles are the data coverage with a 230 km data cut off.

4. Development of a new hybrid technique for the NRL ensemble radar data assimilation system

In FY13, major efforts continued to develop and further improve NRL ensemble radar data assimilation system to enhance Navy’s capability of using the ensemble tool in assimilating storm observations from Doppler radar and other nonconventional meteorological sensors to improve the accuracy in predicting storms of all scales to support Navy operations and weapon systems. Several technical and scientific accomplishments have been achieved. The most significant improvement to the ensemble radar data assimilation system was the development of an innovative hybrid technique that organically combines variational method with the ensemble approach in one data assimilation algorithm, instead of two separate systems, for radar reflectivity data assimilation.

Radar reflectivity assimilation represents one of the major challenges in storm-scale data assimilation due to the zero/non-zero boundaries along the storm edges. In the variational data assimilation method, any phase errors in model storm location forecasts may cause no storm information from the background fields at an observed storm location. This has been verified by the difficulties in bring the missed storms back to the forecast by the variational reflectivity data assimilation system alone. Furthermore, it is very difficult to define the cross-variable background error covariance between the observed reflectivity and the model’s non-microphysical state variables in a variational data assimilation system. In contrast, the ensemble method can estimate the flow-dependent background error covariance between the observed reflectivity and all the model’s state variables. Therefore, not only the microphysical variables but also the dynamical and thermo-dynamical fields of the model are updated simultaneously by the ensemble reflectivity data assimilation. In addition, the ensemble method can patricianly address the zero/non-zero boundary issue by enlarge the coverage of storm areas in the background fields from the ensemble perturbations of storm locations. However, the ensemble spread of storm locations may also create spurious background error covariance outside observed storms, especially when the observation is close to the storm boundaries. It has been

observed that the storm analyses from the EnKF are usually larger and over-smoothed compared to observations.

In the new hybrid technique, two loops of reflectivity procedures are performed. In the first loop, the ensemble means of the model microphysical fields (q_c - cloud liquid water mixing ratio, q_i - cloud ice mixing ratio, q_r - rain water mixing ratio, q_s - snow ice mixing ratio, and q_g - graupel mixing ratio) are used to calculate the ensemble mean of model radar reflectivity. This mean reflectivity usually has larger storm areas than the one from a single forecast due to the ensemble perturbations and when used as background for storm data assimilation, provides more storm information in areas missed by the single forecast due to phase errors. The background field is used in the 3DVAR with a pre-defined background error covariance between the observed and the model's reflectivity fields centered at the observation location with a radius of just one model grid. This basically ensures removal of the spurious storms outside the observed storm areas while the storms within observed storm areas are updated to values closer to the observations. In this procedure, only the model's microphysical fields are updated. In the second loop, the updated ensemble forecasts of microphysical fields are used to compute the flow-dependent background error covariance between the observed radar reflectivity and all model state variables. Since the ensemble mean of the model microphysical forecasts have been enhanced by the 3DVAR in the first loop, the spurious background covariance outside observed storm areas should be reduced. All model state variables are updated at the end of the second loop. Compared to running the EnKF alone, the new technique basically does not increase memory size requirement. The computational cost is also negligible. From the experiments we conducted, the increase in CPU time is usually less than 5 percent. The new technique is currently under test.

5. Progresses were made in assimilating airborne Doppler radar observations

In collaboration with Penn State University funded by ONR, progresses were made in assimilating airborne Doppler radar wind observations into COAMPS-TC with the EnKF. The EnKF and COAMPS-TC were delivered to Penn State University where they were connected to the airborne Doppler radar observations collected by the Hurricane Research Division (HRD) of AOML/NOAA. Experiments have been conducted to test the systems with real data.

RESULTS

The 3DVAR radar reflectivity data assimilation system transitioned to FNMOC has been tested with real-time time for several extensive time periods over a number of domains both over oceans and in CONUS. Figure 2a shows an example of composite radar reflectivity computed from the 3DVAR analyses of the microphysical fields on the WATL 15-km grid and Fig. 2b gives the observed composite radar reflectivity from the WSR-88D network analyzed to the same grid and at the same time. Apparently, the storm information observed by the WSR-88D radars was well assimilated into the model's microphysical analysis fields. This can be seen in the remarkable match between the observed storms and the computed storms both inland and along the US coastal areas (for the storms too far away from the US coastlines, there are no radar observations). Figure 3 shows a similar but more recent case. This is on the 3-km Florida grid. Again, storms in the Gulf of Mexico (west of the Key West) and those off the Florida east coast observed by the WSR-88D radars in the area were fully assimilated into the model and well characterized in the model analyses. For this case, we also looked at the model 12 hour storm forecast (given in Fig. 4a) and compared the forecast to the radar observations at about the same time (Fig. 4b). Please note that the two images in Figs. 4a and 4b are on different grids with different map projections. In this forecast, the COAMPS-OS with radar reflectivity

assimilation had an accurate prediction of the location of the main storm system south of the Tampa Bay while storm intensity forecast looks little stronger than the observations.

Preliminary tests of the new hybrid technique recently developed for the ensemble reflectivity data assimilation also yield some encouraging results. Figure 5a shows the ensemble mean of composite radar reflectivity from the EnKF analyses of 32 members with the new hybrid technique (EnKF-hybrid) for a storm case in June 2005. Figures 5b gives the results from the EnKF analyses without the hybrid technique (EnKF-only). The observed composite radar reflectivity is given in figure 5c for comparison. As you can see, all storms in Figure 5a have been notably improved except the one in South Carolina where the spurious storm seen in the EnKF-only analysis (Fig. 5b) was not changed much by the hybrid technique. The most remarkable improvement in storm analyses can be seen at the left-top corner of the domain where the storms missing in Fig. 5b were brought back to the analyses by the EnKF-hybrid method in Fig. 5a. The enlarged and over-smoothed storm system from the EnKF-only in Fig. 5b (see discussions in the previous section) along the coastal lines of Gulf Mexico has also been notably improved by the EnKF-hybrid technique. But the resulted storms are still not close enough to the observations. To quantitatively evaluate the impact of the hybrid method, equitable threat scores (EQTS) of the composite radar reflectivity analyses in Figs 5a and 5b were calculated against the observations in Fig. 5c as a function of storm intensity (in dBZ) and given in Fig. 6. Obviously, the improvement in the storm analyses is significant.

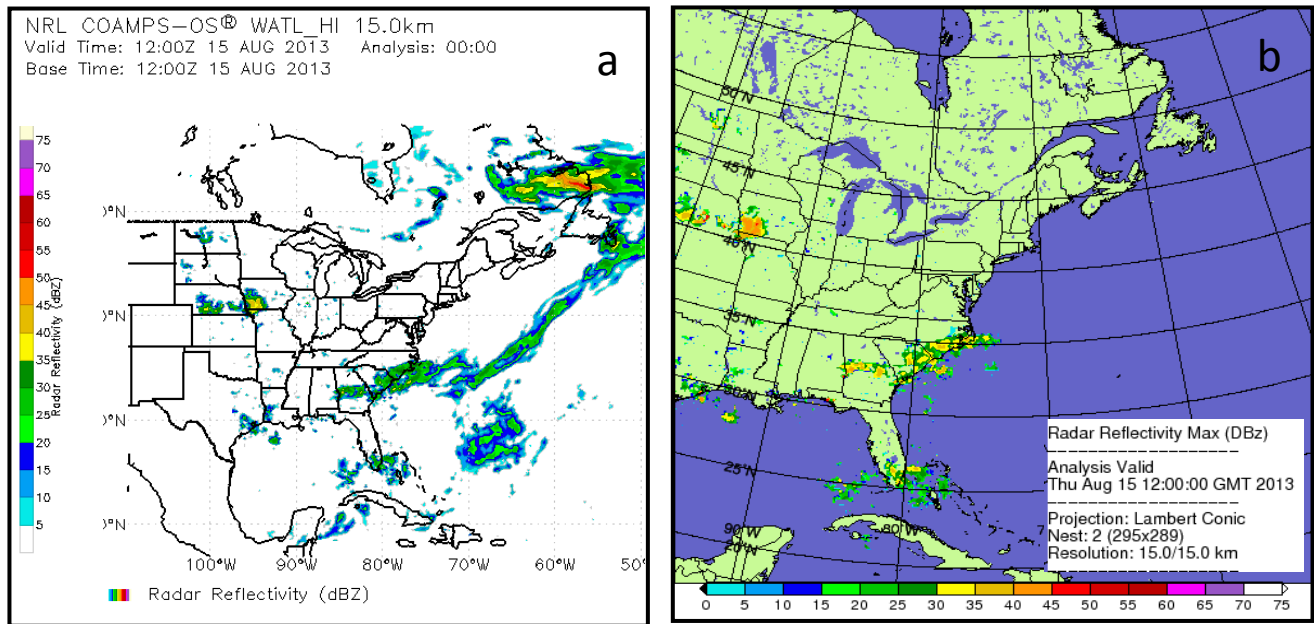


Figure 2. (a) Composite radar reflectivity (dBZ) computed from the COAMPS-OS cloud microphysical analyses on the WATL 15 km grid initialized with the 3DVAR reflectivity data assimilation. (b) The observed composite radar reflectivity from the WSR-88D network analyzed to the same grid.

The impact of the hybrid data assimilation algorithm on ensemble forecasts was also studied. Figure 7a shows the EQTS of the ensemble mean storm location forecasts (defined by 5 dBZ radar reflectivity) as function of forecast hours for the same storm case. Figure 7b are the root-mean-square (RMS) errors of the ensemble mean wind forecasts from the EnKF-only and EnKF-hybrid experiments, respectively.

It appears that the initial improvement in storm locations by the hybrid technique shown in Fig. 6 vanished quickly during the first three hours of the model integration. The positive impact on model wind forecasts, however, was not obvious in the first three hours but became observable during the rest for the 24 hour forecast period. This may have been caused by the latent heat feedback from the improved microphysical processes to the model's dynamics. Since this technique is still under test, more detailed studies will be reported as the research continues.

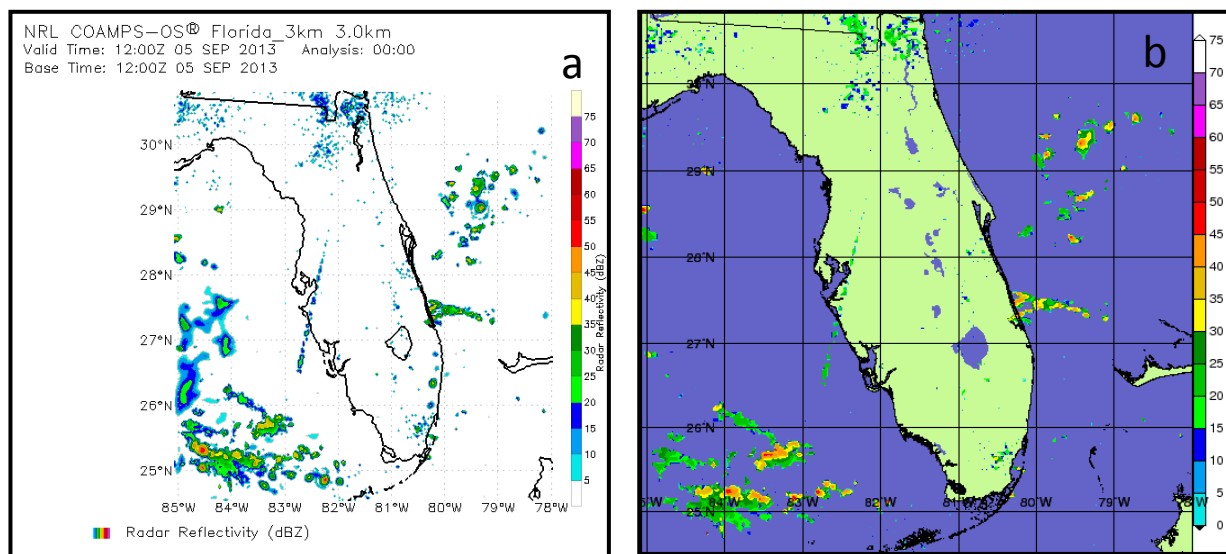


Figure 3. Same as Fig. 2 except for the Florida 3 km grid domain.

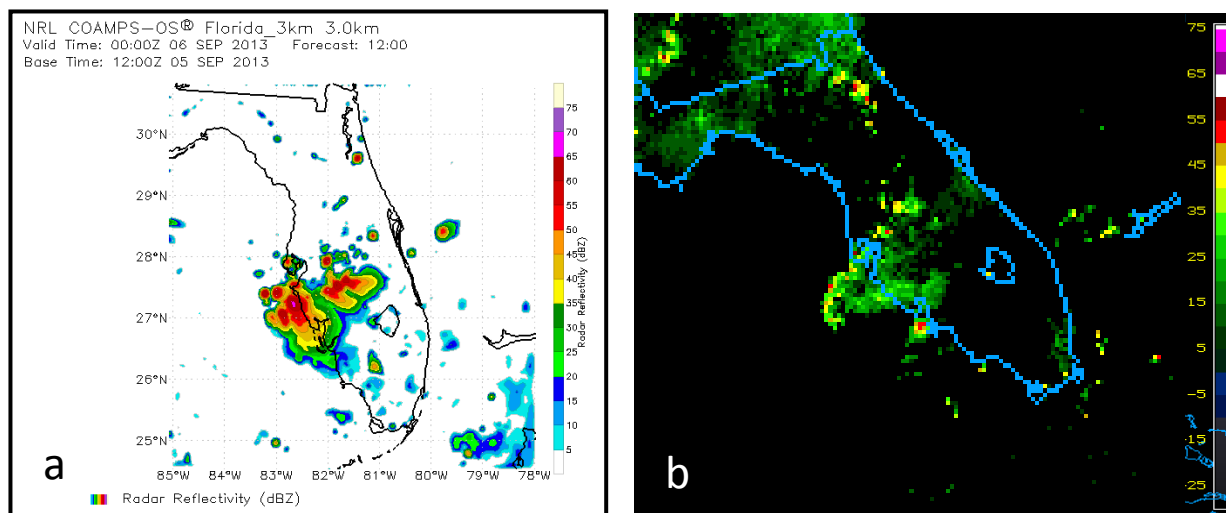


Figure 4. (a) Composite radar reflectivity (dBZ) from the COAMPS-OS 12 hour forecast with the 3DVAR reflectivity data assimilation for the same case as in Fig 3; (b) The observed storms by WSR-88D radars at the same time.

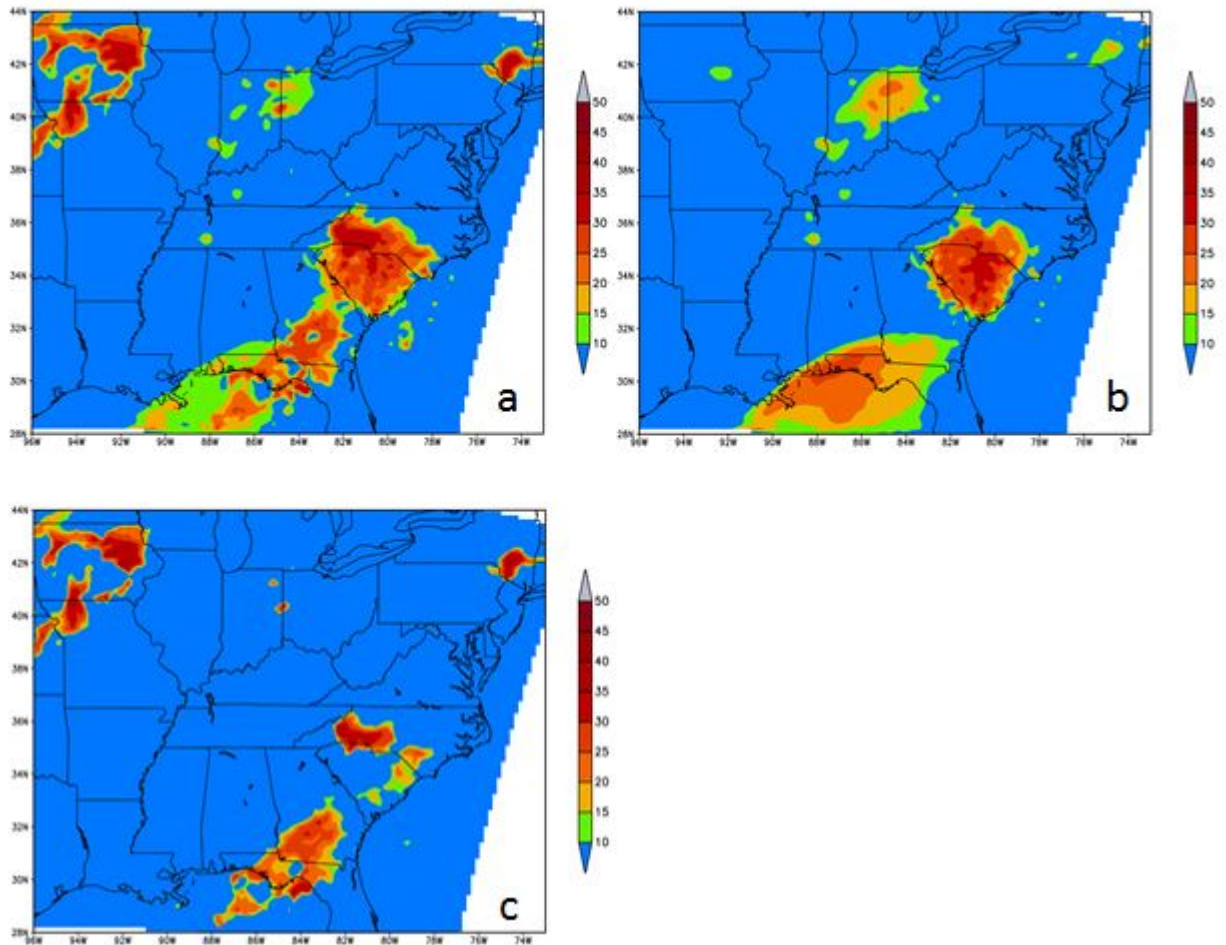


Figure 5. Composite radar reflectivity (dBZ) from the analyses of (a) EnKF-hybrid and EnKF-only (b) for a storm case on 28 June 2005. (c) is the observed storms.

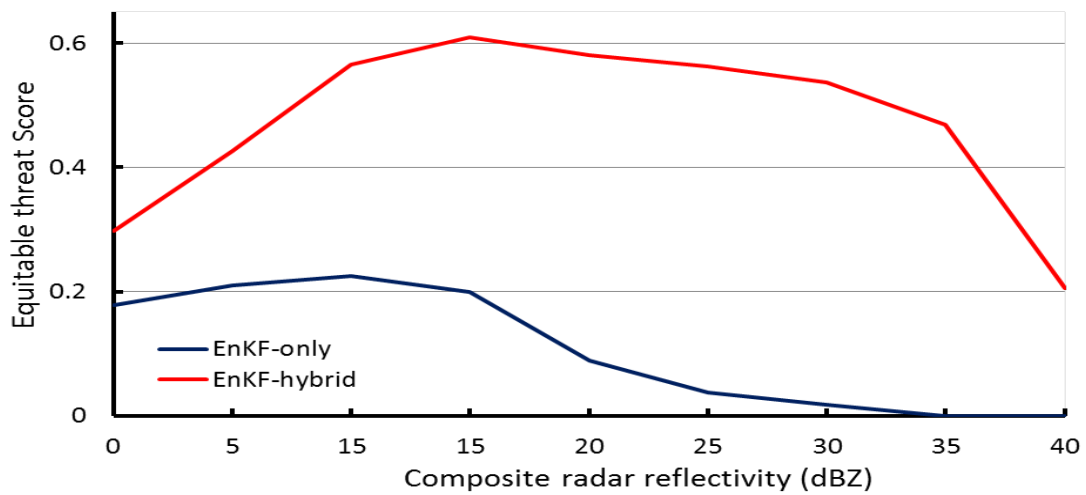


Figure 6. EQTS of the composite radar reflectivity analyses in Figs. 5a and 5b.

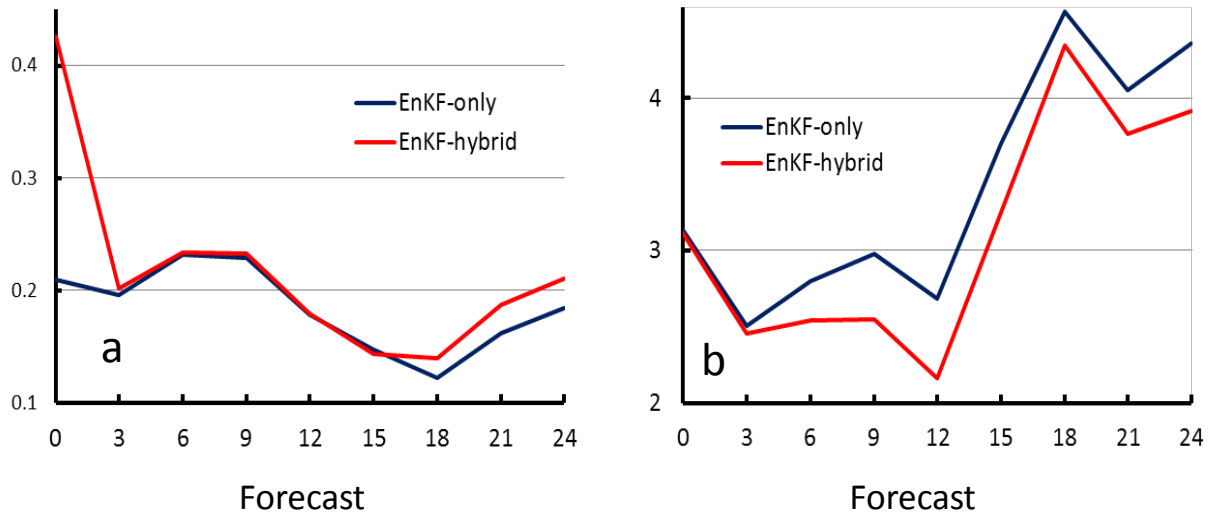


Figure 7. (a) EQTS of composite radar reflectivity forecasts as a function of forecast time from the experiments of EnKF-only and EnKF-hybrid for the same case in Figs. 5a and 5b. (b) RMS errors of the horizontal wind forecasts.

RELATED PROJECTS

6.4 COAMPS-OS (PMW-120).

PUBLICATIONS

- Zhao., Q., F. Zhang, T. Holt, C. Bishop, and Q. Xu, 2013: Development of a mesoscale ensemble data assimilation system at the Naval Research Laboratory. *Wea. And Forecasting* (in press).
- Xu, Q., K. Nai, S. Liu, C. Karstens, T. Smith, and Q. Zhao, 2013: Improved Doppler velocity dealiasing for radar data assimilation and storm-scale vortex detection. *Advances in Meteorology*, doi:10.1155/2013/562386.
- Chen, X., K. Zhao, W.-C. Lee, B.J-D. Jou, M. Xue, and P. R. Harasti, 2013: The improvement to the environmental wind and tropical cyclone circulation retrievals with modified GBVTD (MGBVTD) Technique. *J. Appl. Meteor. Climatol.* (in press).
- Harasti, P. R., 2013: An expanded VVP technique to resolve primary and environmental circulations in hurricanes. *J. Atmos. Oceanic Technol.*, (accepted for publication).

REFERENCES

- Xu, Q., C. J. Qiu, and J. X. Yu, 1995: Simple adjoint retrievals of microburst winds from single-Doppler radar data. *Mon. Wea. Rev.*, **123**, 1822-1833.
- , L. Wei, W. Gu, J. Gong, and Q. Zhao, 2010: A 3.5-dimensional Variational Method for Doppler Radar Data Assimilation and Its Application to Phased-Array Radar Observations. *Advances in Meteorology*, vol. 2010, Article ID 797265, 14 pages. doi:10.1155/2010/797265.

- Zhao., Q., J. Cook, Q. Xu, and P. Harasti, 2006: Using radar wind observations to improve mesoscale numerical weather prediction. *Wea. Forecasting*, **21**, 502-522.
- , J. Cook, Q. Xu, and P. Harasti, 2008: Improving short-term storm prediction by assimilating both radar radar-wind and reflectivity observations. *Wea. and Forecasting*, **23**, 373-391.
- , and Y. Jin, 2008: High-resolution radar data assimilation for Hurricane Isabel (2003) at landfall. *Bull. Amer. Meteor. Soc.*, **89**, issue 9 (in press).